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Integration of Fluid Modeling with Complex-Terrain Field Studies and Model-Development Efforts

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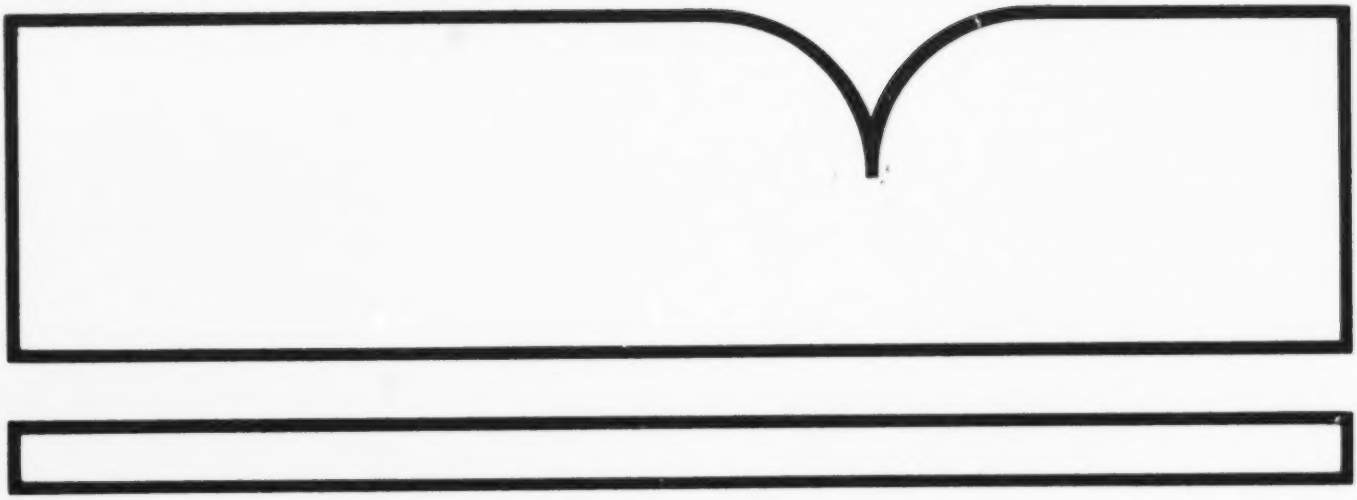

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16. ABSTRACT

EPA's Complex Terrain Model Development Program (CTMDP) was designed to develop reliable atmospheric dispersion models applicable to large pollutant sources located in complex terrain. The primary emphasis was on plume impaction on nearby hills during nighttime stable conditions. EPA's Fluid Modeling Facility (FMF) interacted closely with the model developers participating in the CTMDP and provided support in various ways through the conduct of a wide range of laboratory studies Work at the FMF prior to the inception of the program provided the basic framework for the model - the dividing-streamline concept - and the focal point around which the field program was designed. At the beginning of the program, the FMF provided direct support as an aid to planning the details and strategies of the field experiments and testing the limits of applicability of the dividing-streamline concept. Later work included exercises of "filling in the gaps" in the field data, furthering the understanding of the physical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, testing various modeling assumptions, providing data for "calibration" of various modeling parameters, and testing the ability of the laboratory models to simulate full-scale conditions. The highlights of the FMF contributions to the CTMDP are described herein.

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INTEGRATION OF FLUID MODELING WITH COMPLEX-TERRAIN FIELD STUDIES AND MODEL-DEVELOPMENT EFFORTS

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1. INTRODUCTION

In the late 1970's the Environmental Protection Agency (EPA) identified a crucial need to develop an improved mathematical model that would deal with plume impaction from large sources located in mountainous terrain under stable flow conditions. A workshop was convened in 1979 to focus on complex terrain modeling problems and to develop recommendations to EPA with respect to the design of a program of experiments and model development efforts. Subsequently, the EPA outlined a plan to achieve the objective through an integrated program of model development, fluid modeling experiments and field studies of plume-terrain interactions on hills of progressively increasing size and complexity. This multi-year, multi-faceted program is known as the Complex Terrain Model Development Program (CTMDP). The mathematical model development and field studies were primarily conducted through a contract with Environmental Research and Technology, Inc.

Personnel from EPA's Fluid Modeling Facility (FMF) interacted vigorously with various groups participating in the CTMDP, and provided direct support and guidance in many different ways. The FMF research program has ranged from the development of broad guidelines and physical concepts to specific site studies and regulatory applications. The FMF has provided laboratory data to "fill in the gaps" in the field data and tested the validity of convenient modeling assumptions.

A complete report was prepared (Snyder, 1987) that summarizes the contributions, both direct and indirect, of the FMF to the CTMDP. That report provides a historical perspective and a comprehensive list of FMF's accomplishments with respect to furthering the physical understanding of flow and diffusion in complex terrain. Over 65 publications have been generated from work conducted within the FMF on complex-terrain research. Only a few of the most important publications are highlighted herein.

2. BACKGROUND

The major facilities of the FMF consist of a meteorological wind tunnel and a stratified water channel/towing tank. The wind tunnel has a test section 3.7m wide, 2.1m high, and 18.3m long, and a speed range of 0.5 to 10m/s. The towing tank is 2.4m wide, 1.2m deep and 25m long. It is density-stratified using layered mixtures of salt water.

Research work conducted at the FMF prior to the inception of the CTMDP had a strong influence on the directions to be taken in the field work and on the type of model (*i.e.*, physical concepts) to be developed. The stratified towing tank was commissioned in 1976 and rather fundamental studies were begun immediately on the structure of stably stratified flow over idealized three-dimensional hills and on diffusion from a point source within a stably stratified field of turbulence.

The first published reports on this work described the flow structure observed over a bell-shaped hill under neutral and stably stratified conditions. Earlier theoretical work, model experiments, and observations all indicated that, when the stratification is strong enough, the air flows in approximately horizontal planes around the topography. Up to that time, however, there had been little firm laboratory or field data to suggest how *strong* the stratification must be for any given streamline starting below the hill top to pass *round the side* rather than *over the top* of the hill.

Hunt and Snyder (1980) showed evidence for a dividing streamline of height H_s such that streamlines below H_s would impinge on the hill surface and follow the surface around the sides, whereas streamlines above H_s would go over the top. They suggested the simple formula

$$H_s = h\,(1 - F) \qquad (1)$$

as the criterion to determine whether a plume embedded in the flow approaching the hill would impact on the surface or surmount the top, for $0<F<1$ ($F=U_\infty/Nh$ is the Froude number, where U_∞ is the approach-flow wind speed, N is the buoyancy frequency, and h is the hill height). This formula was demonstrated through towing-tank experiments to be valid for a linearly stratified environment and a uniform approach-flow velocity profile.

This formula provided the basis for a simple conceptual model (Hunt et al, 1979) that was used as the framework for the Complex Terrain Dispersion Model (CTDM) and, indeed, as the framework for the design of the CTMDP. This conceptual model divides the flow-field into two regimes, a lower layer below the dividing-streamline height which flows in essentially horizontal planes around the hill -- this flow may thus be described in terms of two-dimensional flow around a cylinder -- and an upper layer above the dividing-streamline height which may be described in terms of a modified potential flow over a cut-off hill.

Snyder *et al* (1980) presented further evidence from towing-tank experiments in support of the simple formula; they showed it was applicable to other shapes of axisymmetric hills, namely a cone and a hemisphere. Furthermore, they presented another simple formula and supporting experimental data for determining whether an elevated (step) inversion would surmount a hill. This second formula, which predicts the point at which the interface just reaches the hilltop, is

$$\frac{U_\infty^2}{(g h_o \Delta\rho/\rho_1)} = 2\left[\frac{h}{h_o} - 1\right], \qquad (2)$$

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where g is the acceleration due to gravity, h_o is the height of the interface (far upwind), $\Delta\rho$ is the density difference across the interface, and ρ_1 is the density of the fluid between the interface and the surface.

The "state of the science" immediately prior to the contract award was as follows. The dividing-streamline concept had been shown to be a useful conceptual framework to use in describing the structure of strongly stratified flow around three-dimensional hills. It had only been shown to be valid, however, for quite a limited range of hill shapes, all of which were axisymmetric. It had only been verified under uniform stratification (linear density gradient) or under a step inversion (sharp density interface), under a uniform approach-flow velocity profile, and, of course, only under steady-state, small-scale laboratory conditions.

3. RESULTS AND DISCUSSION

The major CTMDP contract was awarded in June, 1980, and the work plan called for the small hill impaction study to begin at Cinder Cone Butte (CCB), Idaho, in September. Almost immediately, the FMF conducted towing-tank experiments to aid in the detailed planning and design of the field experiments. The first study provided guidance with regard to the location of the main meteorological tower. A second study provided guidance for developing smoke- and tracer-release strategies, for preselecting locations for samplers and cameras, and for choosing in advance several different sampler strategies to account for variations in flow regimes and wind fields. A third study tested the validity of an integral formula for predicting the dividing-streamline height.

In anticipation of the field study at CCB, the question arose as to how to predict the dividing-streamline height when the wind profile was not uniform and the density gradient was not linear. This was of paramount importance in planning the release scenarios, as the release locations and heights were to be chosen in real time during the field study based upon the incoming real-time meteorological data. J.C.R. Hunt immediately proposed the now well-known integral formula as

$$\frac{1}{2}\rho U_\infty^2(H_s) = g\int_{H_s}^{h}(h-z)\left(-\frac{\partial\rho}{\partial z}\right)dz. \qquad (3)$$

This integral formula is based upon simple energy arguments. It answers the question: "in a strongly stratified flow approaching a hill, does a particular fluid parcel at some height upstream possess sufficient kinetic energy to overcome the potential energy required to lift itself through the density gradient from its upstream elevation to the hill top?" If not, then it clearly must pass around the hill. The left-hand side may be interpreted as the kinetic energy of the parcel far upstream at elevation H_s, and the right-hand side as the potential energy gained by the parcel in being lifted from the dividing-streamline height H_s to the hill top h through the density gradient $d\rho/dz$. This integral formula was presumably applicable to a fluid with any stable density profile and, presumably, with any approach-flow velocity profile. In practice, it must be solved iteratively, because the unknown H_s is the lower limit of integration; the formula can easily be reduced to the simpler formulae (1) and (2) using the boundary conditions applicable to those special cases. The third study thus attempted to verify this integral formula under density profiles similar to those expected at CCB.

A typical nighttime temperature profile in the Snake River Basin (site of CCB) was found to consist of a strong, surface-based inversion of depth 50 to 100m and a weaker inversion above extending to several hill heights. Hence, the stratified towing tank was filled with a strong density gradient near the surface and a weaker gradient above. A vertical rake of 3 tubes was positioned well upwind of the hill (a model of CCB), and neutrally buoyant dye was emitted from each tube. For each tow, a particular stack height (center tube) was chosen and the general formula was integrated numerically using the measured density profile to predict the towing speed required such that the center streamer would rise to the elevation of the saddle point of CCB, *i.e.*, the minimum height of the draw between the two peaks. If the formula were correct, then, the lower streamer should go round the side of the hill, the upper streamer should go over the top, and the center one should split. The height of the break-point between the two gradients was then reduced and the process repeated. In all, twelve tows were made, varying the height of the break-point or the dividing-streamline height (release height) each time.

Figure 1 shows a side view of the impinging streamers during a typical tow, *i.e.*, the upper streamer going through the draw, the lower streamer going round the side, and the middle one splitting. The agreement between the predictions and observations was excellent. The results of this set of experiments provided confidence in the validity of the general integral formula for predicting the height of the dividing streamline for a wide range of stable density profiles. The onsite computers were thus programmed to calculate the dividing-streamline heights using the incoming real-time meteorological data during the field experiments. This proved to be a great benefit in terms of categorizing the flow fields and in interpreting observations of plume behavior. Later analyses of the data strongly supported the dividing-streamline concept.

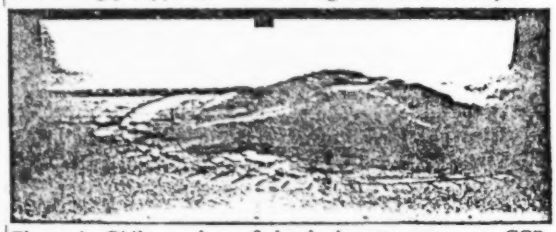

Figure 1. Oblique view of impinging streamers on CCB. Middle dye streamer is released at the dividing-streamline height; others at ±1cm (±6m full scale).

Subsequent to the field study, one particular hour of the field data at CCB was selected for simulation in the towing tank. That hour was 0500 to 0600, 24 October 1980 (Case 206), which may be characterized as very stable, *i.e.*, light winds and strong stable temperature gradients. Measurements made during the towing-tank experiments included ground-level concentrations under various stabilities and wind directions, vertical distributions of concentration at selected points, plume distributions in the absence of the hill, and visual observations of plume characteristics and trajectories.

This series of tows showed that the surface-concentration distributions were extremely sensitive to changes in wind direction. For example, Figure 2 shows that the distribution shifted from the north side of the hill to the south side with a shift of only 5° in wind direction. Comparisons of individual distributions with field results showed much larger maximum surface concentrations and much narrower distributions in the model results. To account for the large variability in the winds measured during the hour, a matrix of 18 tows

(three wind directions × six wind speeds) was conducted, and the concentration patterns were superimposed. The resultant superimposed model concentrations compared very favorably with field measurements. The largest model concentrations were within a factor of two of the highest field values, and 70% of the model concentrations were within a factor of two of the corresponding observed field values.

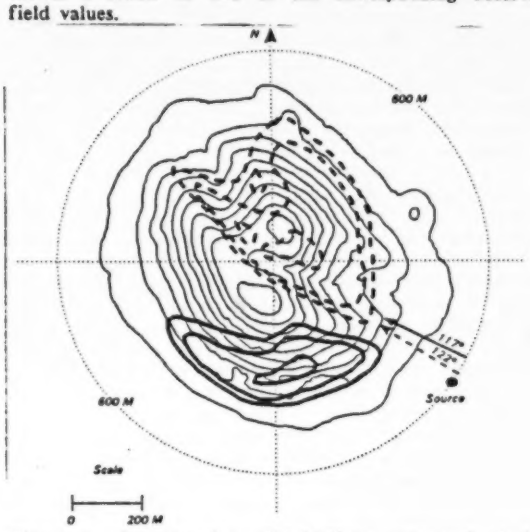

Figure 2. Concentration distributions measured during individual tows of CCB with H_s/h=0.31 and H_D/h=0.38; wind direction: ——— 117°, – – – 122°.

The extreme sensitivity of plume trajectory to wind direction correlated well with the field observations. In numerous instances, especially during the most strongly stable conditions (when plumes were released below the dividing-streamline heights), the plumes were observed to flip-flop several times from one side of CCB to the other during the course of an hour, *i.e.*, the plumes were never observed to impinge directly on the hill surface for a duration longer than a few minutes at a time. The apparent magnitudes of these wind-direction shifts (as indicated by the changes in plume direction) were much larger than the wind-direction shifts indicated at towers somewhat remote from the hill.

Numerous other studies were conducted to test the validity and limits of applicability of the dividing-streamline concept, for example, examining the effects of shear in the approach-flow velocity profile, of the crosswind aspect ratio of the hill, of the hill slope, and the effect of the wind angle on a long ridge. These results were published separately as parts of papers on studies done for a variety of different purposes, but the specific aspects dealing with the validity and applicability of the dividing-streamline concept were extracted and published collectively by Snyder et al (1985).

In response to a request from the model developers, a series of measurements was made of plume characteristics in flat terrain and over a three-dimensional hill immersed in the simulated neutral atmospheric boundary layer of the meteorological wind tunnel. Effluent was released at a number of elevations, upwind distances, and positions laterally offset from the centerplane determined by the wind direction and the center of the hill. Sufficient concentration measurements were made to enable the construction of plume cross sections at the downwind position of the hill center and, in a few cases, at the upwind base of the hill. These data were analyzed to provide the desired information on horizontal and vertical plume deflections and deformations effected by the hill. One of the more dramatic examples is shown in Figure 3. In this case, the source was on the centerplane at ground level, 6 hill heights upwind of the hill center (the skirt of the hill extended to 5h). Plume cross sections measured at the position of the center of the hill, both in the presence and in the absence of the hill, are shown. The hill effected a 91% increase in the lateral plume width. In this case, the maximum surface concentration (at the same downwind distance) was decreased by a factor of 2 but, of course, the area of coverage by large concentrations was greatly increased. Detailed data reports were provided to the model developers immediately, and the results were published by Snyder and Lawson (1986).

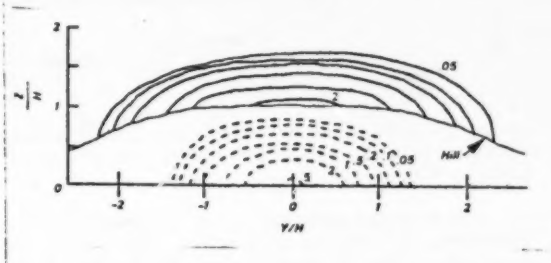

Figure 3. Plume cross sections measured in presence (———) and in absence (– – –) of axisymmetric CCB model at x=0 (hill center). H_s/h=0, x_s/h= -6, y_s/h=0.

As a result of these and similar measurements, refinements were made to CTDM. Specifically, the calculation procedures were modified to use the strain inferred or measured over the crests of two- and three-dimensional hills in the laboratory, *i.e.*, the parameters in the model were adjusted in accordance with laboratory data. Substantial improvements to the CTDM predictions were obtained, as described by Strimaitis and Snyder (1986).

The second phase of the CTMDP involved a field study at a very long (two-dimensional) ridge, Hogback Ridge (HBR) in New Mexico. Prior experimental studies conducted at the FMF had suggested that steady-state conditions were not established in a towing tank with strongly stratified flows (say $F < 1$) approaching two-dimensional ridges. Two different physical mechanisms give rise to this unsteadiness; one is called "squashing", the other, upstream wave propagation. Very brief explanations will be given here; the interested reader should consult the cited references.

The squashing phenomenon is most easily described in terms of the simple energy arguments as used in deriving Equation 3. As discussed there, a fluid parcel with insufficient kinetic energy to overcome the potential energy requirement to surmount the hill must pass round the sides of the hill. But a two-dimensional hill has no sides around which to pass (in a towing tank, a "two-dimensional" hill is one that spans the entire width of the tank). Hence, the fluid must come to rest. In the tank, since the fluid is generally at rest and the hill is towed, this means that the fluid ahead (upstream) of the hill must be pushed ahead of the hill. However, the upstream endwall of the tank prohibits this fluid from being pushed. Hence, the fluid between the hill and the upstream endwall is "squashed" as the hill approaches the endwall. Because the fluid is incompressible, it must rise and spill over the top of the hill, just as water in a bucket will rise and spill over the top when the sides are squashed.

Upstream wave propagation may also occur in stratified flows, both in the field and in the laboratory. Such motions, if present, will modify the approaching flow. These disturbances take a sinusoidal form in the vertical, the "mode" (number of oscillations) being dependent upon the Froude number based upon the depth of the tank. An example of the deformation of a vertical dye line upstream of a model is shown in Figure 4. Further work to better understand the nature and causes of these upstream motions is described by Castro and Snyder (1988).

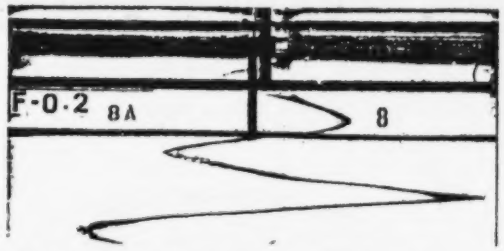

Figure 4. Deformation of vertical dye line by upstream motions. A model hill is approaching the viewing area from the bottom right.

The squashing phenomenon has no counterpart in the atmosphere, as there is no "endwall" forcing the flow toward the ridge. Upstream wave propagation, however, does occur in the atmosphere. These motions result in "blocking" and "upstream influence". However, in the tank, these upstream waves are reflected from the endwalls of the tank and return to modify the flow locally around the model hill; this reflection from the endwalls does *not* have a counterpart in the real atmosphere.

Because of these unsteadiness problems, the FMF input to the experimental design of the HBR study was restricted to neutral wind-tunnel and weakly stratified towing-tank flow-visualization experiments prior to the field study. These laboratory studies provided information on (a) plume height above the surface over the ridge crest and at the upstream edge of the ridge, (b) the apparent size of the plume deformations upwind of the hill, (c) lee wave importance and structure, and (d) sensitivity of the plume trajectory to "wind angle". This information was subsequently used by the field designers to guide the design of the smoke and tracer-gas release protocols at HBR, and to help select sampler and camera locations. Blocking and upstream influence were clearly evident during the field observations at HBR.

4. SUMMARY

The EPA Fluid Modeling Facility has conducted a wide range of laboratory studies and a limited amount of numerical modeling of flow and diffusion in association with the Complex Terrain Model Development Program. Work at the FMF prior to the inception of the program provided the basic framework for the model - the dividing-streamline concept - and the focal point around which to design the field program.

Throughout the course of the CTMDP, the FMF interacted vigorously with the model developers by providing support in various ways. Early work provided direct support in planning the details and strategies of the field experiments and solidifying and testing the limits of applicability of the dividing-streamline concept. Later work included exercises of "filling in the gaps" in the field data, furthering the understanding of the physical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, and testing the ability of the laboratory models to simulate full-scale field conditions. And, as the needs arose, the FMF tested various modeling assumptions, concepts, and hypotheses and provided data for "calibration" of various parameters within the CTDM model.

The most significant contributions included (1) the conceptual framework for the mathematical model (*i.e.*, the division of the flow-field into two regimes, a lower layer below the dividing-streamline height which flows in essentially horizontal planes around the hill, and an upper layer above the dividing-streamline height which is treated as modified potential flow over a cut-off hill) and the detailed experimental validation and establishment of limits of applicability of these concepts, (2) verification of the integral formula for the height of the dividing streamline -- this allowed computations of the dividing-streamline height under arbitrary approach-flow conditions, including shear in the approaching wind-speed profile and nonlinear temperature gradients, (3) demonstration of the extreme sensitivity of surface concentration patterns to wind direction under strongly stratified conditions, (4) measurements of plume deflections and deformations over hills in neutral flow -- these permitted adjustment of the parameters in CTDM and resulted in substantial improvements in the CTDM predictions, and (5) further defining the limits of applicability of laboratory facilities to simulating strongly stratified flows over long ridges.

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